Biomass Imaging for Research on Carbon and Habitats (BIRCH)*

A mission concept for ESSP AO-4

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* With assistance/contributions from Jim Abshire, Jack Bufton, David Smith, Jan Gervin, Forrest Hall, Ted Grems, Bryan Blair, Jonathan Rall, Diane Wickland, the IMDC, the GSFC Carbon Cycle Team, the EX-6 Post-2002 mission study team, the NGBL concept team, the VCL mission team, and participants in the recent workshop "Multi-Dimensional Forested Ecosystem Structure: Requirements for Remote Sensing Observations,,

Biomass Imaging for Research on Carbon and Habitats (BIRCH)

Science Objectives

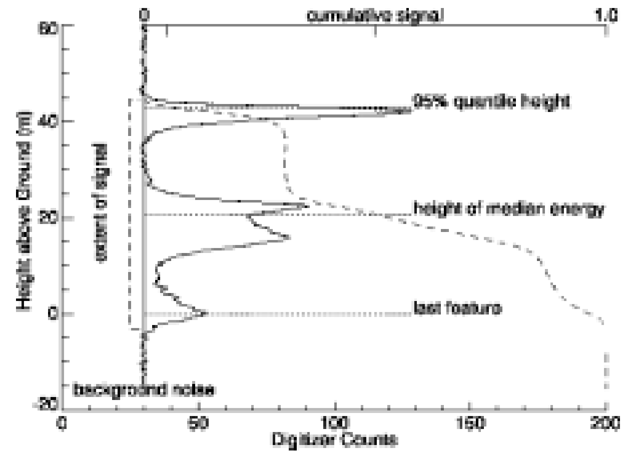
- First globally consistent biomass inventory: this would reduce uncertainty of the carbon stock in above ground biomass from roughly ± 100 Pg (at least ± 50 Pg) to less than ± 10 Pg.
- Measure habitat quality associated with vertical structure and identify biodiversity effects of simplified vertical structure. (Meets requirements for a spectrum of biodiversity and habitat studies and national applications.)
- Provide vertical structure data to improve modeling of ecosystem responses to global change and prediction of global carbon cycles.

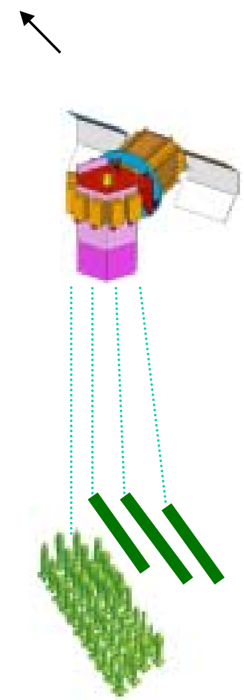
(Listed in descending order of priority.)

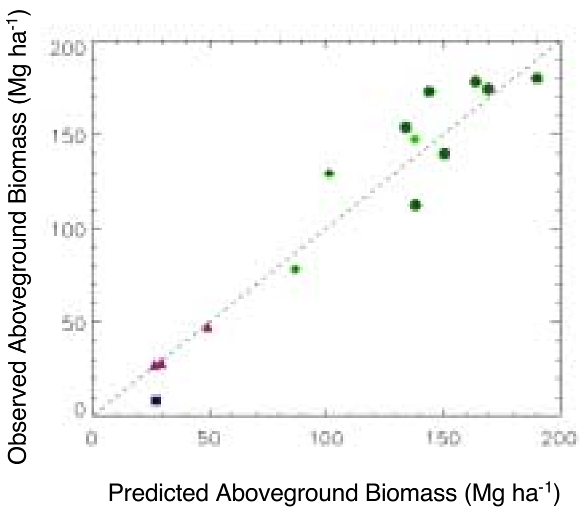
Relevant Earth Science Enterprise Questions

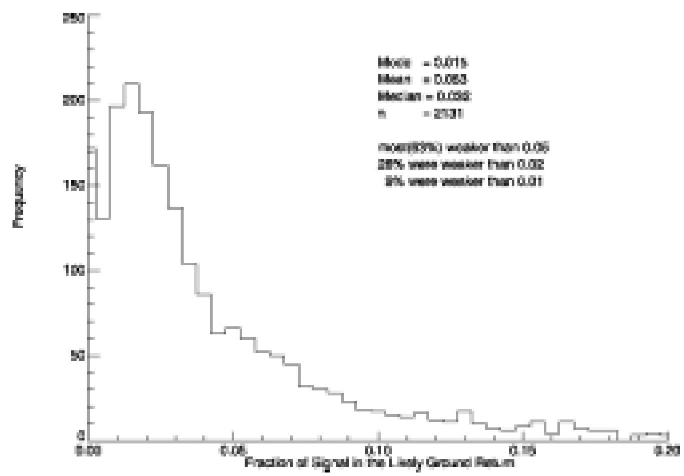
- How are global ecosystems changing?
- What changes are occurring in global land cover and land use, and what are their causes?
- How do ecosystems respond to and affect global environmental change and the carbon cycle?
- What are the consequences of land cover and land use change for the sustainability of ecosystems and economic productivity?
- How well can cycling of carbon through the earth system be modeled, and how reliable are predictions of future atmospheric concentrations of carbon dioxide and methane by these models?

Measurement Concept



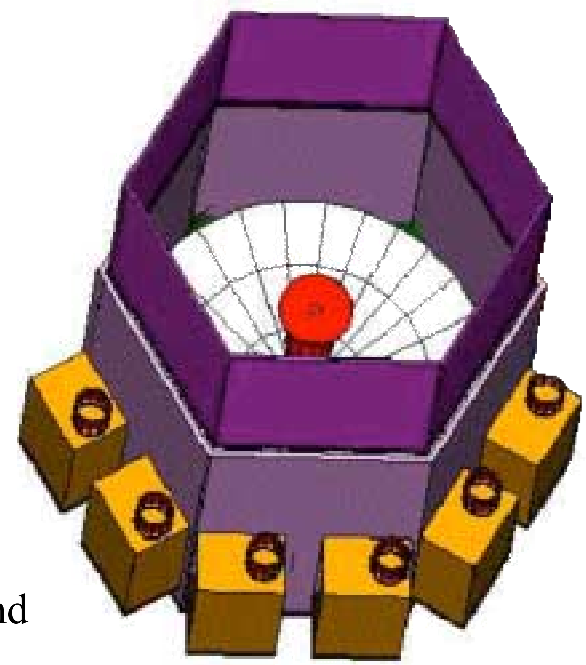






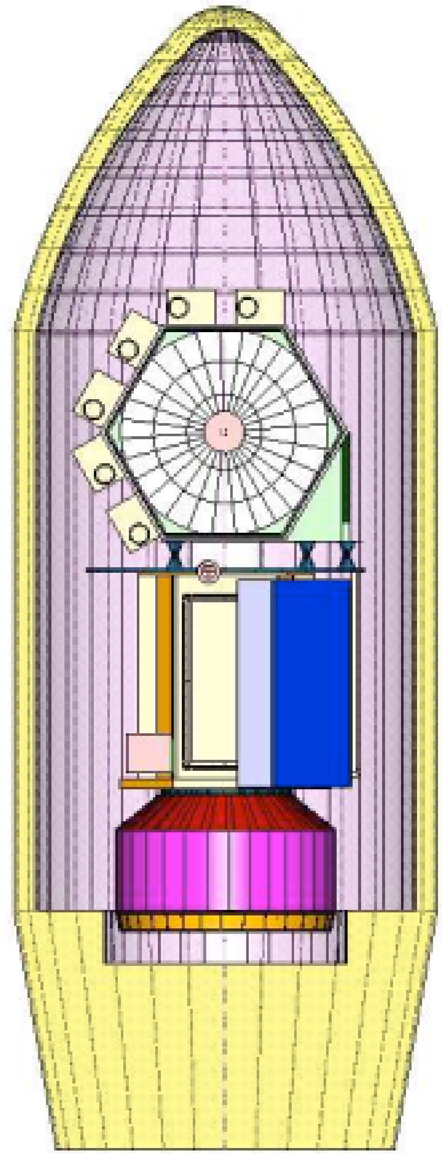
Carbon Cycle Study: Instrument Characteristics

- Six nadir-pointing 1.064 micron wavelength, solid-state lasers
  (4 active, 2 spare), 75 meter spot size, 100 pulses/sec
- 1.5 meter Be telescope
- Detectors: 3x3 Si APD arrays
  (20 x 20 meter pixels each)
- Instrument envelope (stowed): L: 2.0 meter,
  W: 1.7 meter, H: 1.9 meter
- Mass: 312 kg
- Power: 500 W during data collection,
  100 W standby
- Data Rate: 6.7 Mbps peak, 3.7 Mbps average
- Duty cycle: 30% average, 42% peak--only over land

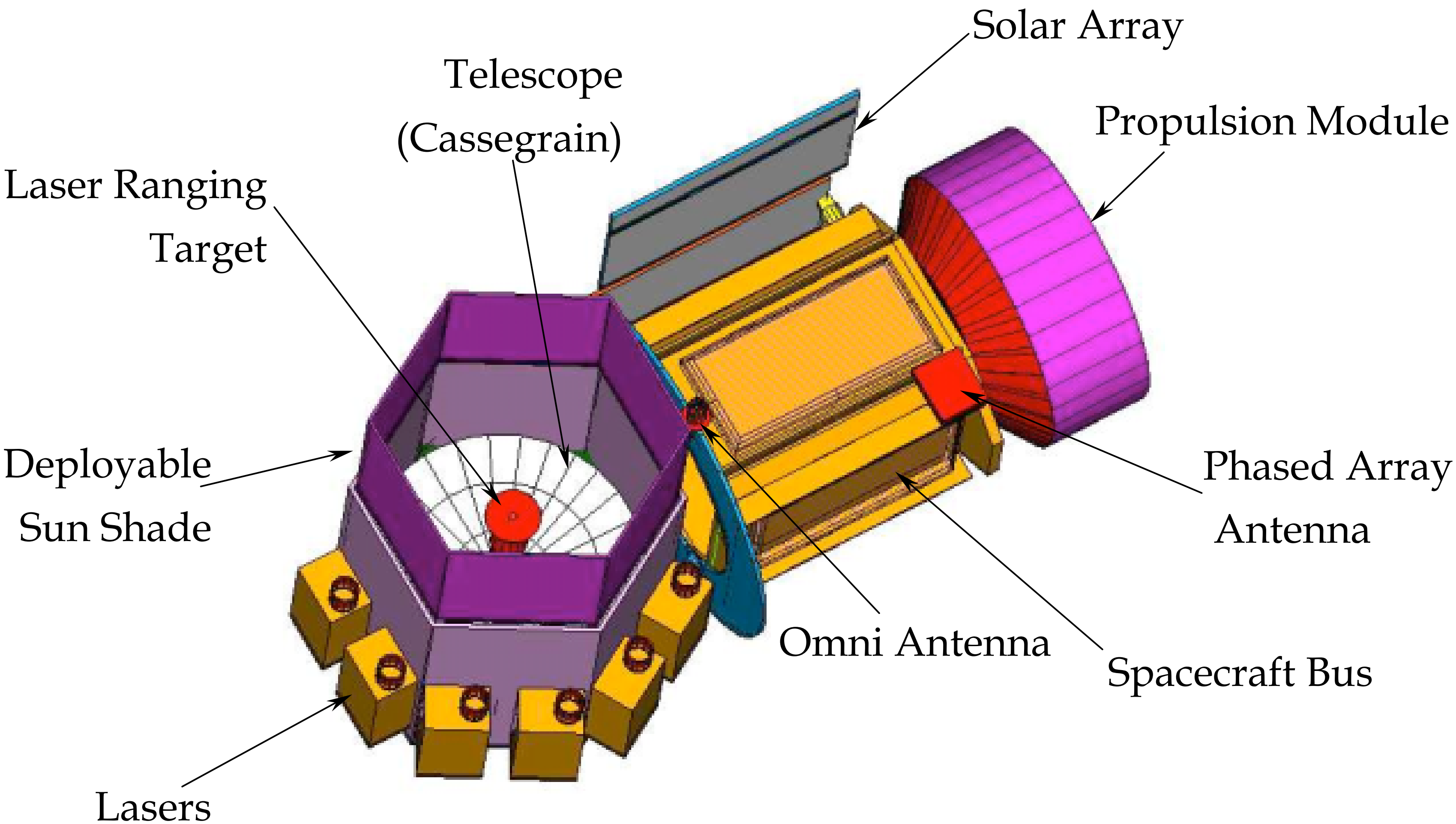


Carbon Cycle Study: Mission Characteristics

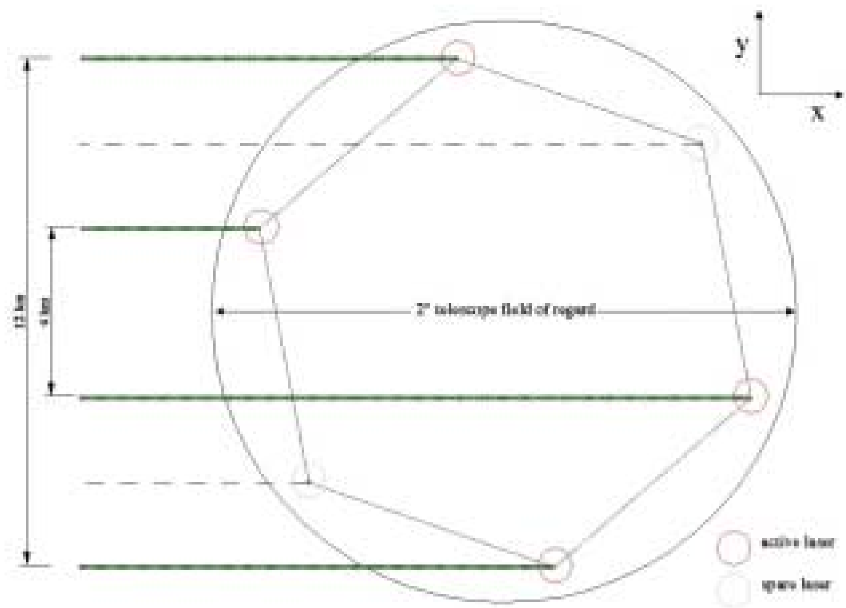
- Orbit: 400 km, sun-synchronous, 6pm ascending node
- ACS: Nadir pointer, 3-axis stabilized, arc-sec knowledge
- Launch Mass: 941 kg including 196 kg of hydrazine
- Power: 719 W during data collection, 319 W standby
- 3.7 Mbps average
- Mission envelope (stowed): L: 4.5 meter, W: 2.2 meter, H: 2.4 meter
- Launch vehicle: Delta 2320-10

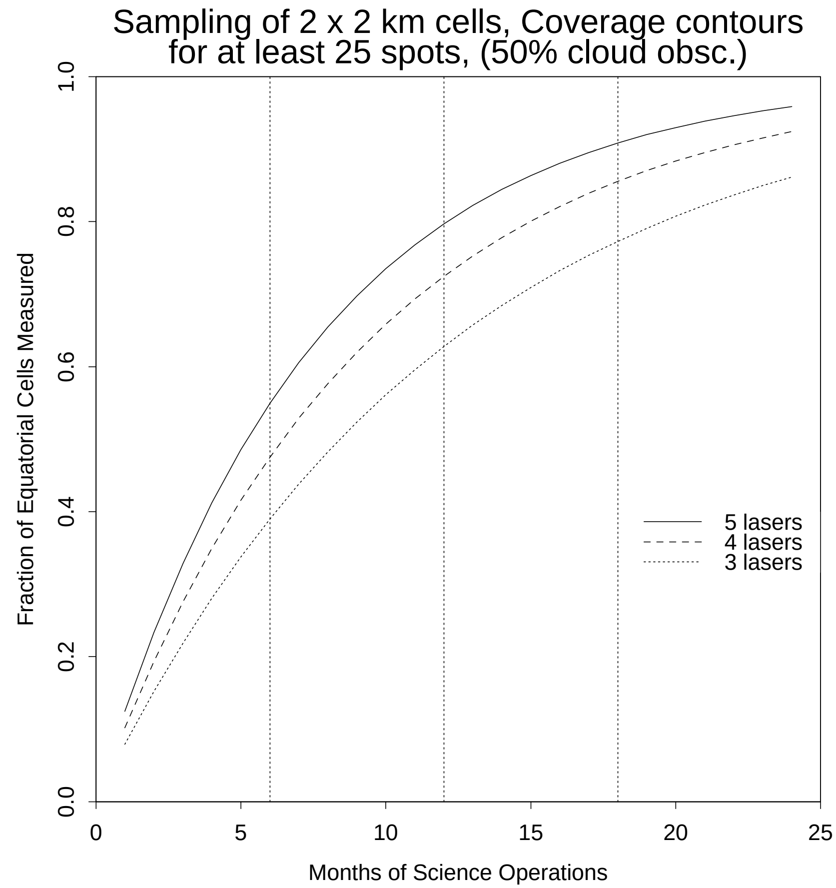


Carbon Cycle Study: Mission Concept



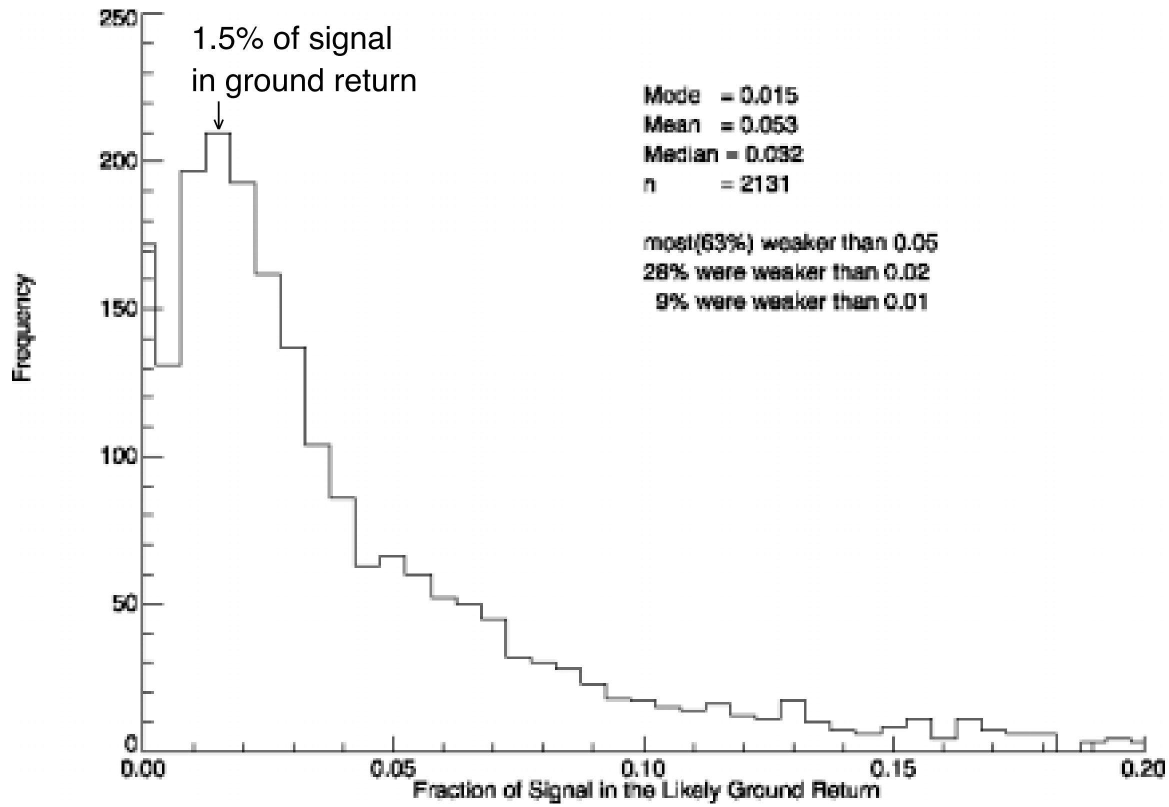
Multiple laser ground tracks accelerate mapping of a regular grid





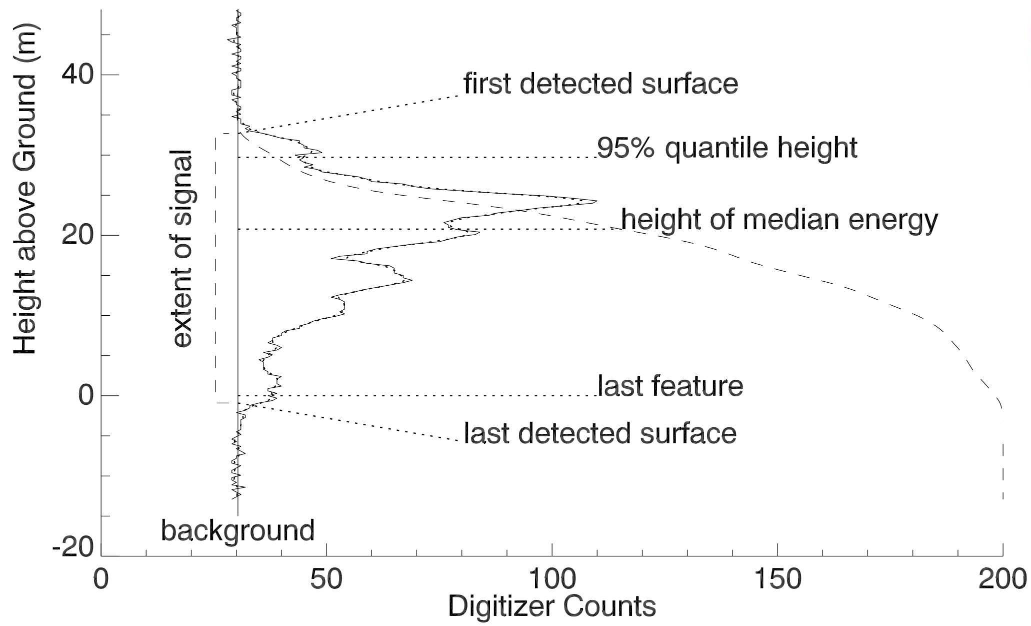
(Knox, 1998, prepared for VCL mission)

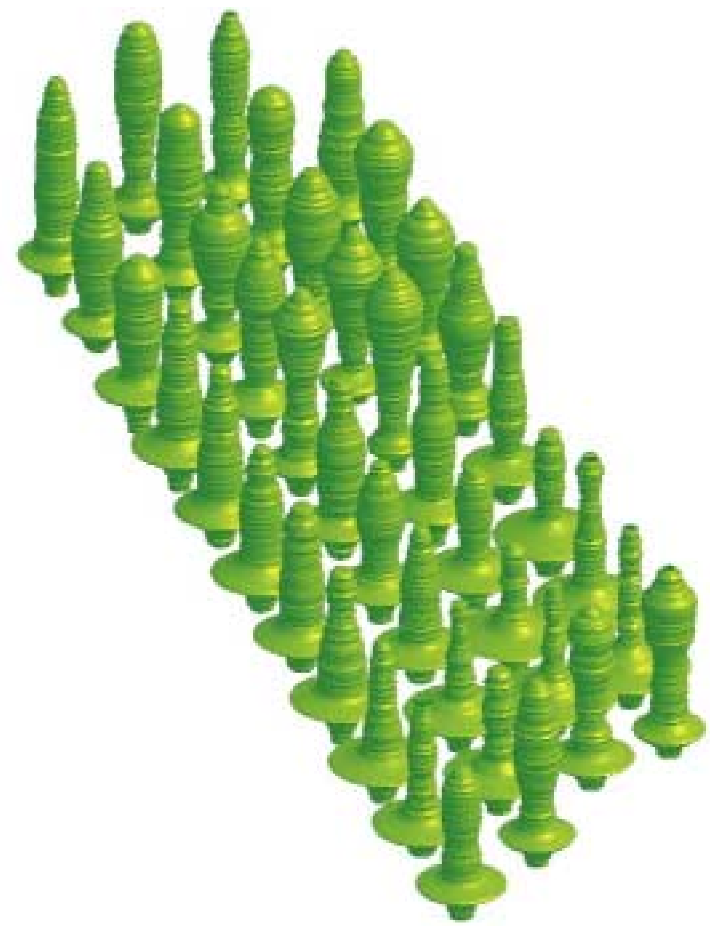
Tropical rainforest has low penetration of overhead illumination to the ground surface



We calculated relative energy in portions of the nearest lidar waveforms (within 10 m horizontal distance) at the elevation of survey monuments under dense tropical forest at La Selva Biological Station in Costa Rica. Zero (0.) values were assigned to the 5% of cases where lidar data did not extend low enough for a valid energy estimate. (Knox & Blair, 2000, prepared for the VCL mission)

Across-track imaging adds context





[LVIS data from central MD, Oct. 1997, volumes of rotation for √(amplitude) Knox, 2001, unpublished]

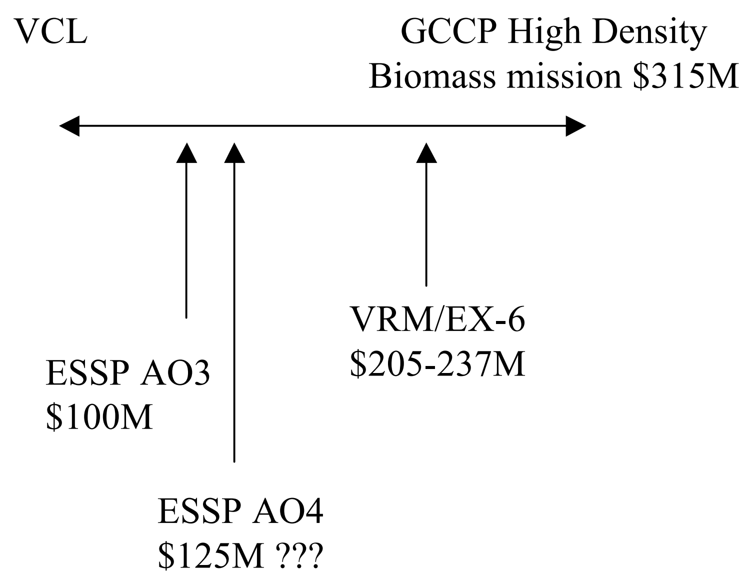
New BIRCH Requirements Traceability (draft)

Science Objectives	Scientific Measurement Requirements	Instrument Functional Requirements	Mission Functional Requirements (top level)
1a. Reduce uncertainty of carbon stock in above ground biomass from ± 100 Pg to ± 10 Pg. 1b. Reduce uncertainty in C fluxes from on-going land cover change by 50%.	- 1 ha patches to ± 10% 25x25 km averages to < 5% - residual biases < 5% - globally valid calibration to above ground biomass (at ~1 ha scale) - complete tropical forest coverage (sampling)	- 10 m to 20 m pixels - at least 25-pixel blocks (0.25-1.0 ha in area) - at least 100 independent blocks in 25 km grid cell - estimate ground slopes (±3º along and across track) - detect subcanopy ground > 0.5% of signal	- LEO orbit (450 to 550 km) - 24-month design life - dawn-dusk orbit (re S:N and power) vs. low inclination for tropical coverage - 3-axis control - TBD instrument power - TBD data rate
2. Measure habitat quality and identify biodiversity effects of simplified vertical structure.	- vertical profile data resolve features with 5 m vertical separation - canopy heights ± 2 m - canopy volume/cover - subcanopy openness	- measurement bandwidth > 100 Mhz (< 10 ns) for feature separation, < 5 ns for feature location	- half-pixel geolocation for data fusion (est. component reflectances)
3. Improve modeling of ecosystem responses to global change.	- canopy heights horizontal variation in canopy structure - sunlit/shadowed foliage	- adjacent waveforms at 10-20 m horizontal resolution or point detections at 1-3 m horizontal resolution	- seasonal near-repeat (e.g., 90-day)

Context for Mission Sizing

- ESSP cost cap: \$100M to \$125M?
- Biomass pathfinder, focused on providing a first comprehensive global inventory of above ground biomass stocks
- *cf.* high-end lidar instruments studied for Post-2002 and carbon cycle planning (± 1-3 Pg)
- Global sampling (no SAR)
- No firm requirement for *separated* laser ground tracks
- 24-month mission adequate
- A simple imaging lidar could be a viable alternative to a new VCL proposal

Costs (excluding launch services)



Some options for lidar biomass imaging

Lidar Design Options

- Large spots (GLAS-like) centered on an imaging detector array
- Single-pixel detectors fiber-coupled to form a focal-plane array

- “Whisk broom„ array of Nd:YAG lasers firing in sequence, e.g., de-rated from GLAS laser design
- Push-broom array/ribbon of Er:Yb fiber lasers synchronously pulsed at ≥1 kHz (freq. doubled to ~775 nm)

What approach is both low-risk and strategic for NASA?

Performance Levels

- *Baseline:* 12 m pixels, 8 × 8 array, center-weighted energy distribution, near-contiguous

- *High option:* 10 m pixels, 10 wide, 100 m continuous swath

- *Low option:* 20 m pixels, 4 × 4, 250 m spacing (~28-112 pps)

- *Threshold:* 25 m pixels, 2 × 2, 1 km spacing (~7-28 pps)

BIRCH Pre-formulation work

Have IMDC study results for a 'high end' BIRCH mission concept

- (1.5 m aperture, 6 lasers, 500W, ~300 kg, 400 km orbit, 3-year mission life, etc.)
- Used Bufton-Knox instrument concept, developed scaling MBLA design
- Not compatible with ESSP cost cap (3X!).

Scientific community working to quantify and refine requirements

- Workshop held June 23-25, 2003
- Review papers for a special issue, pending
- Working group under discussion

Propose a study to define a robust, low-risk instrument concept and initial design.

Requires(?): Instrument Scientist, Science Lead, Instrument/mission Systems Engineer; followed by work to retire remaining risk associated with the selected concept.

Mission definition team:

(1) Mission pre-formulation team with: Formulation Manager, Instrument Scientist, Science lead, Mission Systems Engineer, Instrument Systems Engineer/Designer, Laser reliability lead, Instrument data electronics lead, other expertise TBD.

(2) Proposal team: add mission partners, ground systems expertise, other discipline engineers.

ISAL/IMDC beneficial after baseline instrument concept and narrowed trade-space.

A Spectral-Ratio Biospheric Lidar

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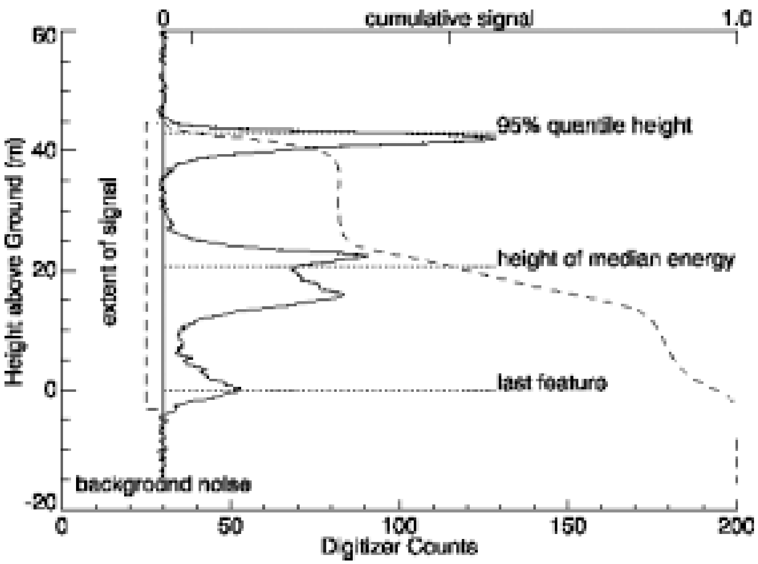
March 18, 2004

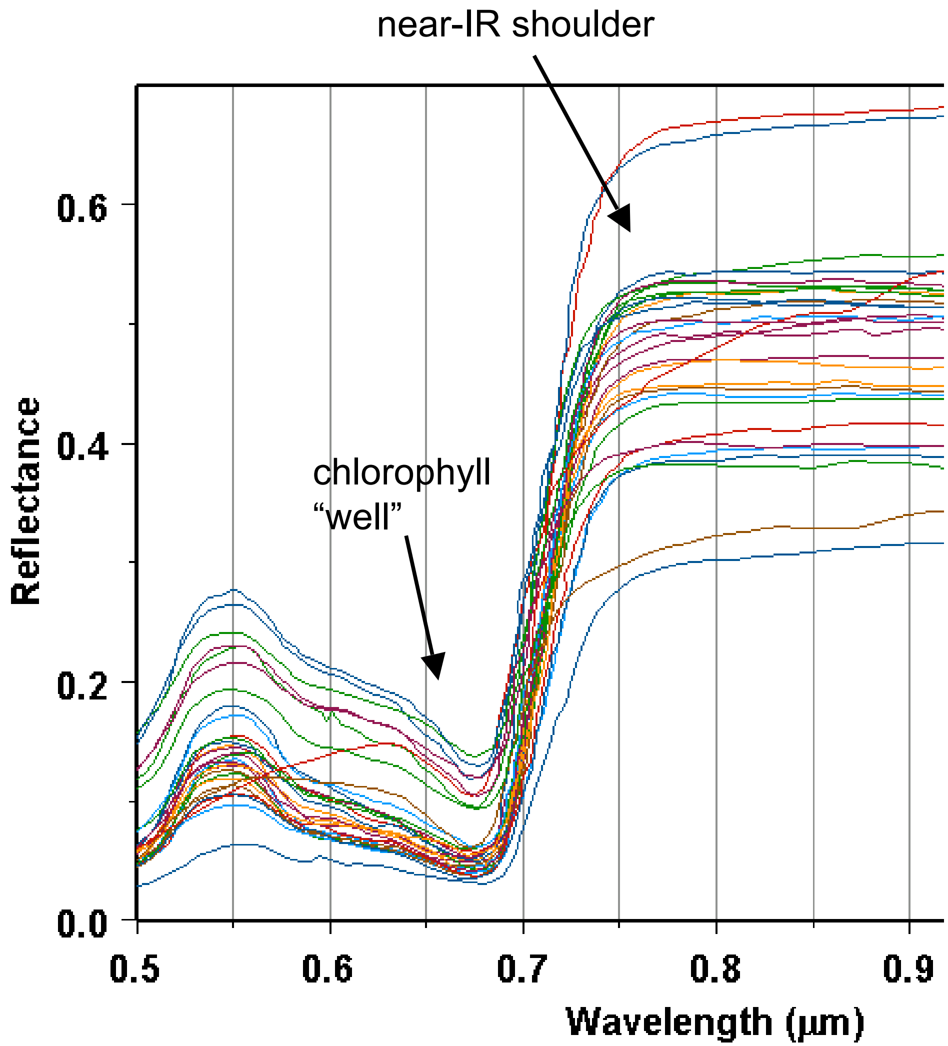
Lidar measurement of canopy properties

With a single frequency, pulsed lidar, the roughness of vegetation distorts and extends the signal from a short pulse. Here a tropical forest lidar waveform (24 m laser spot) shows the complex signal from a dense plant canopy.

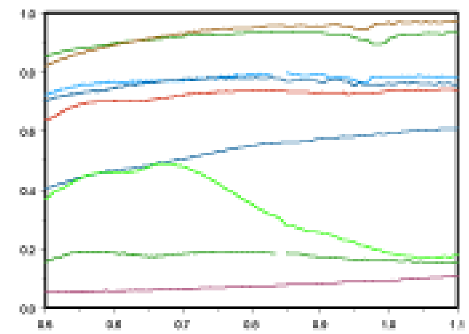


Single-frequency lidar cannot distinguish vegetation from other sources of roughness at the same scales. (Commercial lidar firms working to combine lidar with high-resolution multispectral data.)

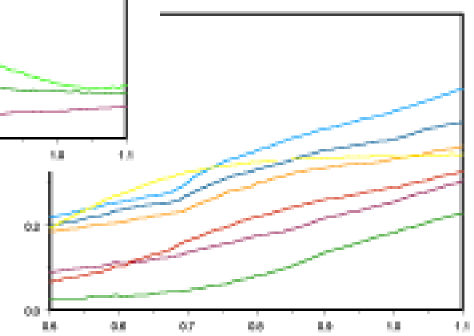
Contrasting Near-IR and red reflectance in spectra from healthy leaves are the basis of vegetation Indexes



Leaf and bark spectra are from the Superior National Forest
(Hall et al. 1992. NASA TM 104568)



Soil minerals



Bark and leaf litter

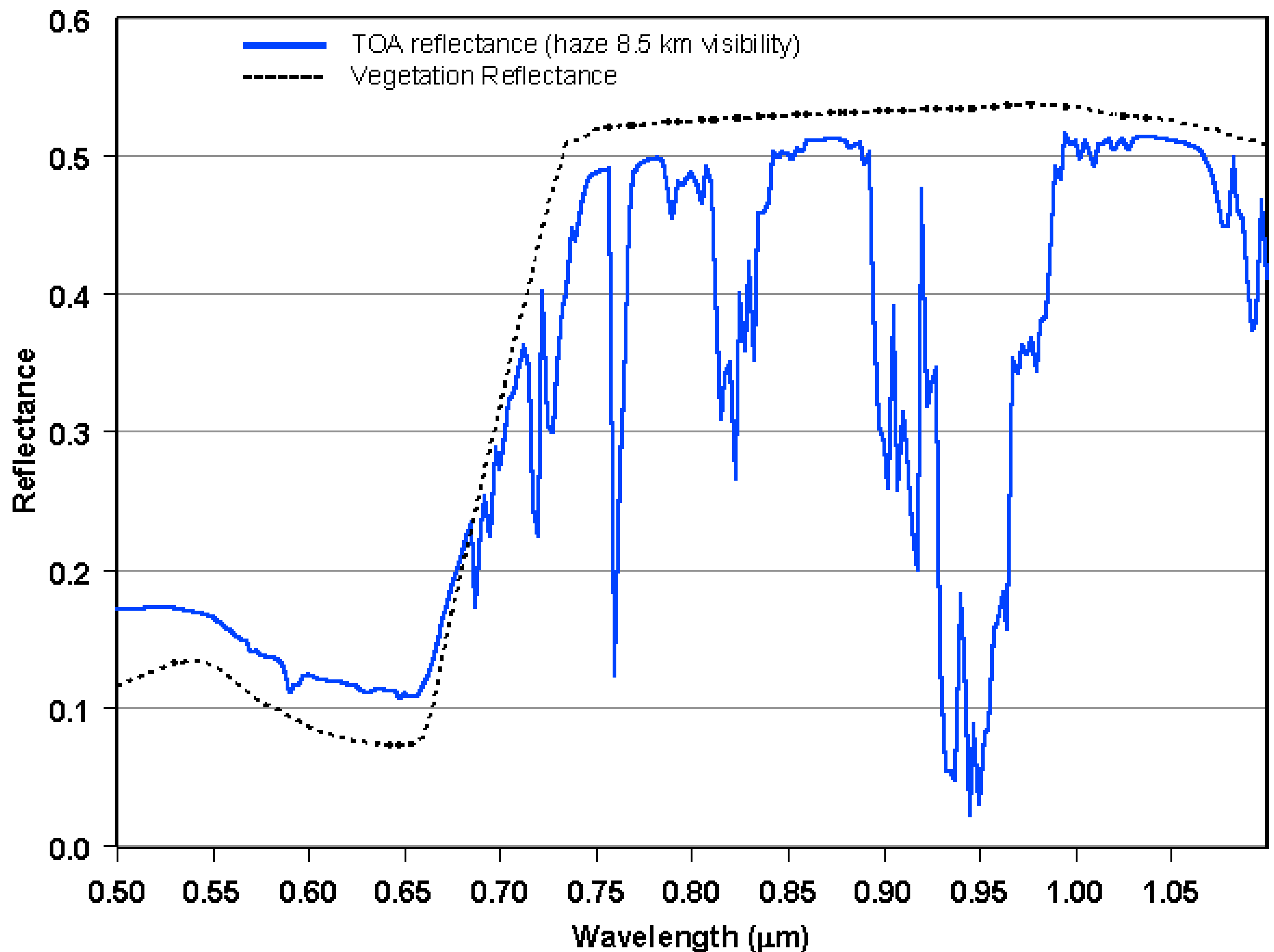
NDVI $\frac{(\rho_{NIR} - \rho_{red})}{(\rho_{NIR} + \rho_{red})}$

SR $\frac{\rho_{NIR}}{\rho_{red}}$

SAVI $\frac{(1+L)\cdot(\rho_{NIR} - \rho_{red})}{(\rho_{NIR} + \rho_{red} + L)}$

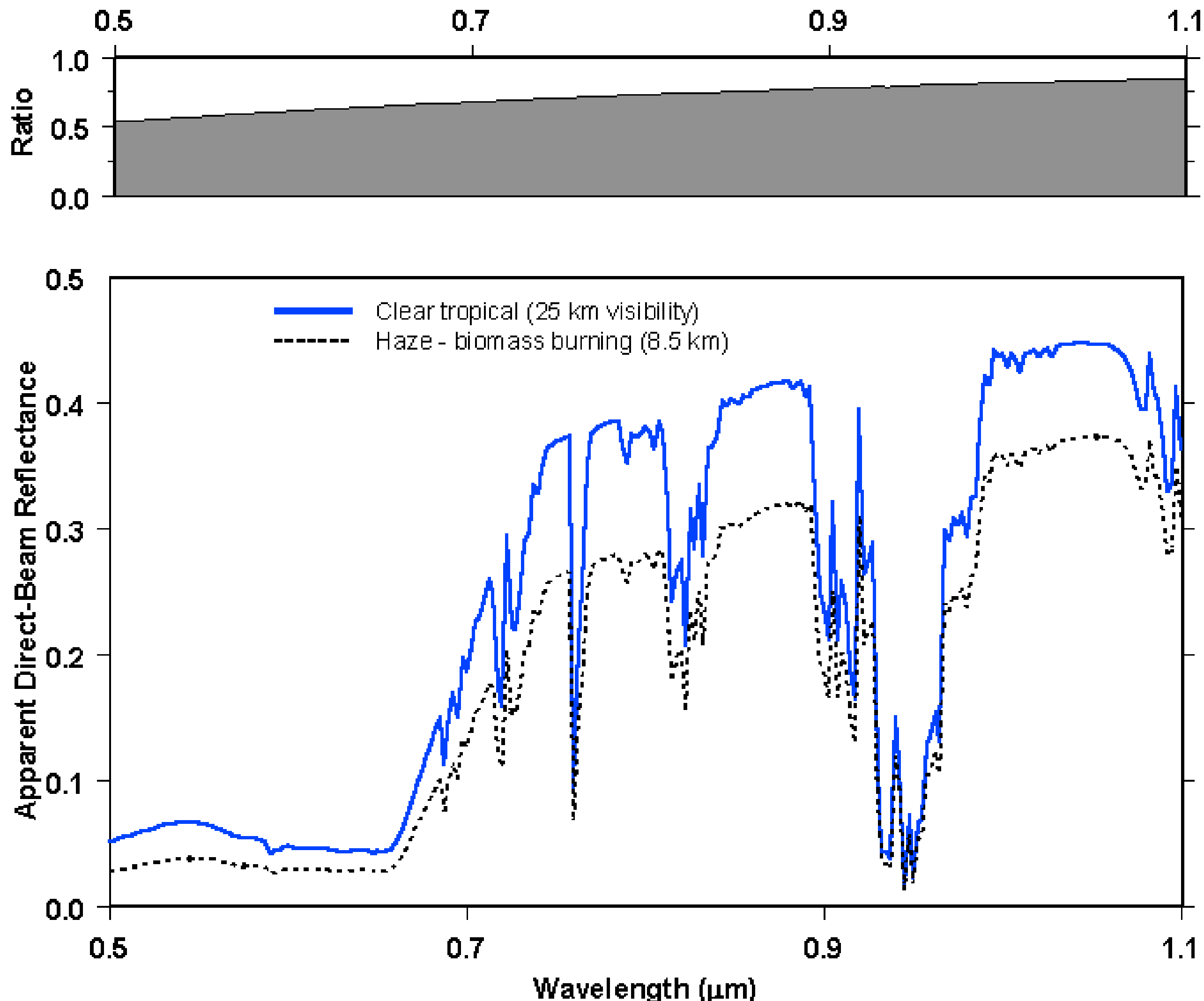
(from Knox & Rall, 2002)

Atmospheric scattering and attenuation reduce visible-NIR contrasts in passive optical images (6S model - nadir view)



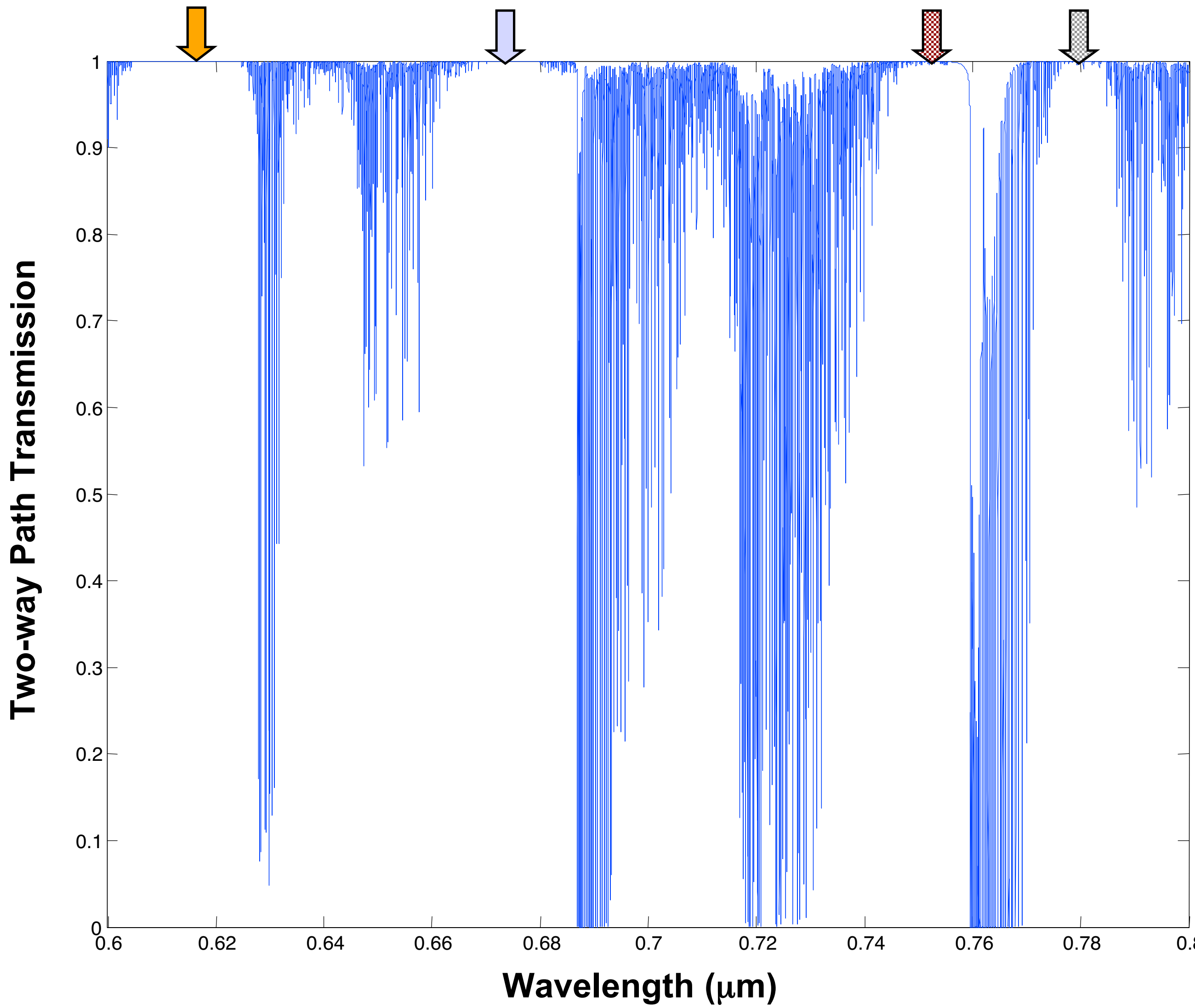
(from Knox & Rall, 2002)

Reflectance ratios of direct-beam signals, i.e. lidar using nearby wavelengths, can be robust to atmospheric variation



(from Knox & Rall, 2002)

Water vapor and oxygen lines leave 4 windows especially suitable for a spectral-ratio biospheric lidar



(2-way atmospheric path calculated with GENSPECT and HITRAN 2000 database, Knox & Rall, 2002)

Spectral Ratio Biospheric Lidar—Proof-of-Concept Instrument

Transmitter

- Dual semiconductor laser transmitters
  - 660 nm / 40 mW
  - 780 nm / 70 mW
- Pulsed operation:
  - 100 nS pulsewidth
  - 250 kHz PRF (4 uS period)

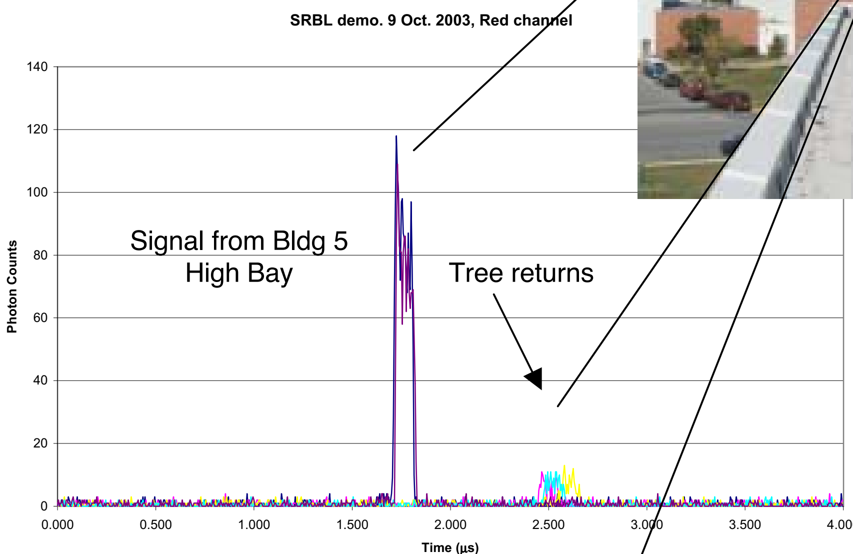
- Dichroic beam splitter used to combine out going beams
  - Overlap near and farfields

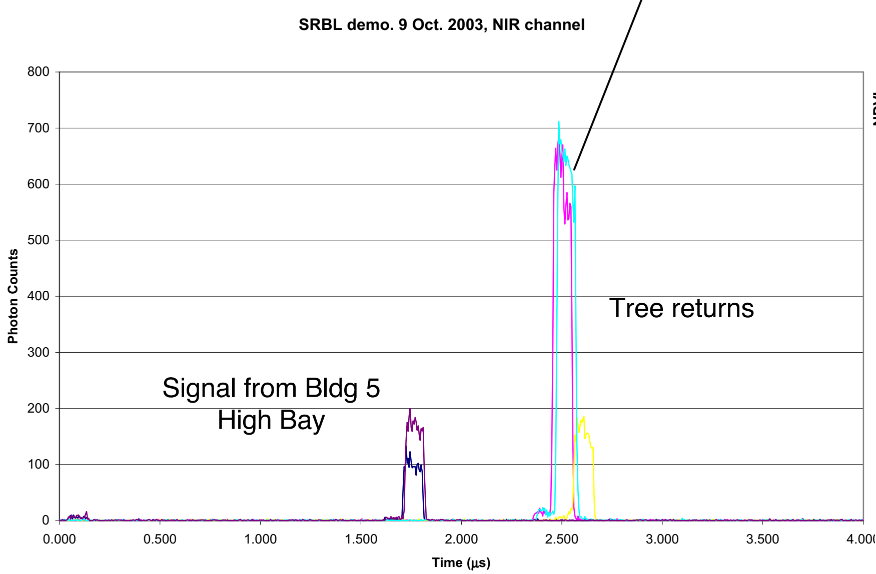
Receiver

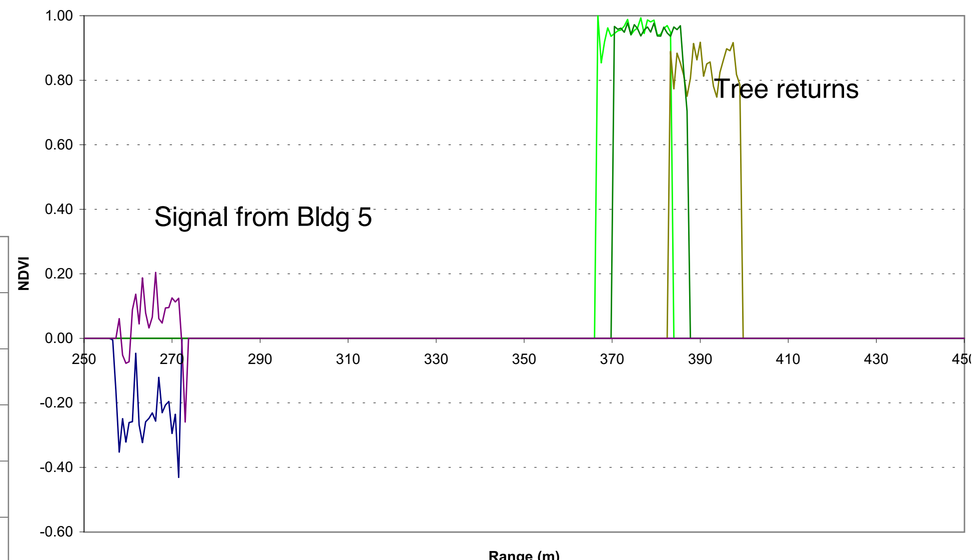
- 20 cm diameter Schmidt-Cassegrain telescope
- Dichroic beam splitter, splits received light into 660 & 780 nm channels
- Fiber-coupled single photon counting modules
- EG&G Turbo Multichannel Scaler / PC

SRBL Demonstration Measurements

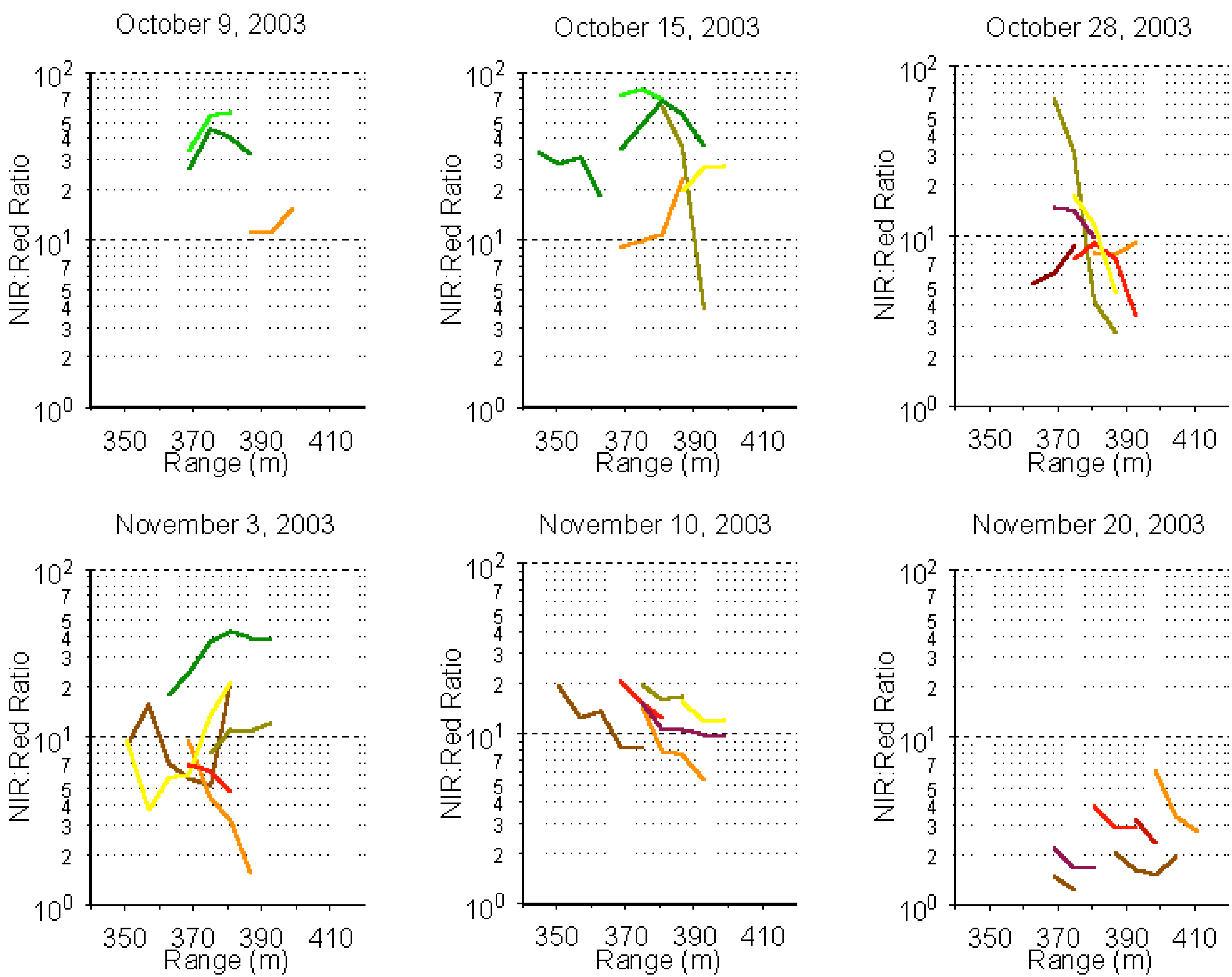
- Transmit power
  - NIR (781.1 nm) ~ 1.5 mW avg
  - Red (658.5 nm) ~ 0.8 mW avg
- Calibration target - side Bldg 5
  - NIR & Red returns ~equal
  - Detector responsivity offsets xmit power difference
- Tree returns - NIR >> Red
  - Healthy, green foliage absorbs Red, strongly reflects NIR







$$\mathrm{NDVI} = (\mathrm{NIR}-\mathrm{Red})/(\mathrm{NIR}+\mathrm{Red})$$


October 9, 2003
October 15, 2003
October 28, 2003
November 3, 2003
November 10, 2003
November 20, 2003
NIR:Red Ratio
Range (m)
10^0
10^1
10^2
2
3
4
5
7
350
370
390
410

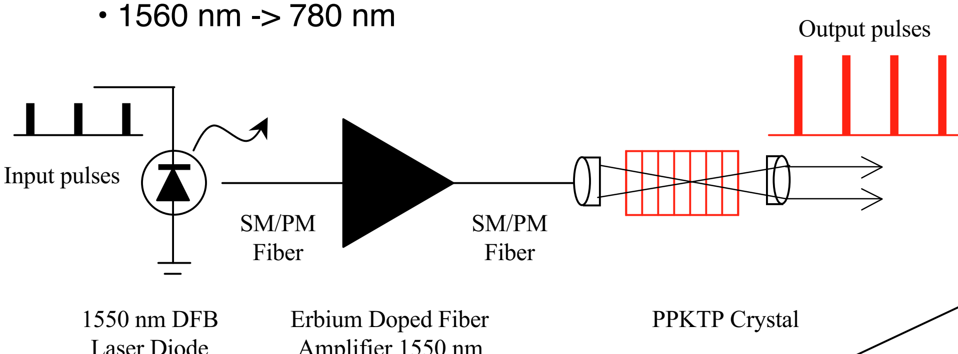
Spectral Ratio Biospheric Lidar—Power Scaling

5 Watt (37 dBm) Erbium doped fiber amplifier

- 1540-1570 nm - flat gain curve
- Polarized single mode input
- Polarized input/output - improves freq doubling
- Directly modulated DFB seed laser to pulse amp
- 100nS-1uS pulse width / 1-15 kHz PRF

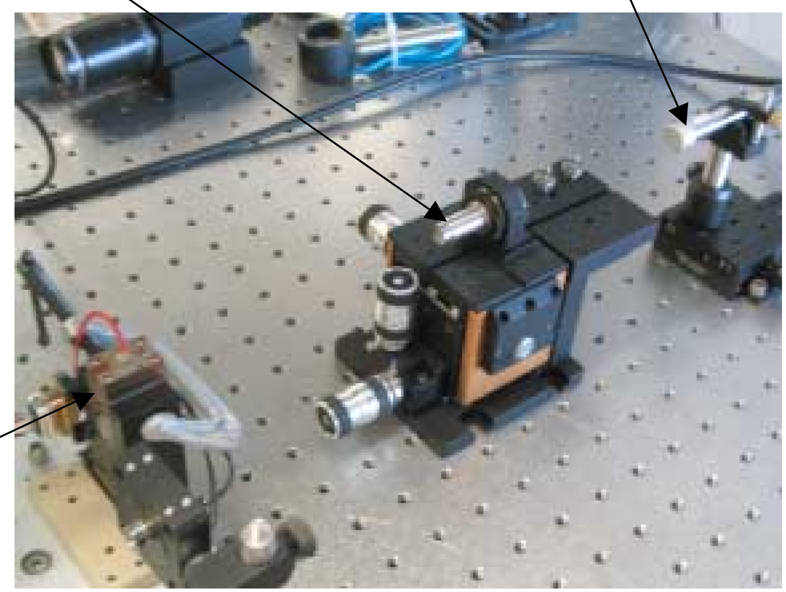
Frequency doubling with Periodically Poled KTP

- Efficient (>50%) frequency doubling
- 1560 nm -> 780 nm



Focusing optic

Fiber amp output

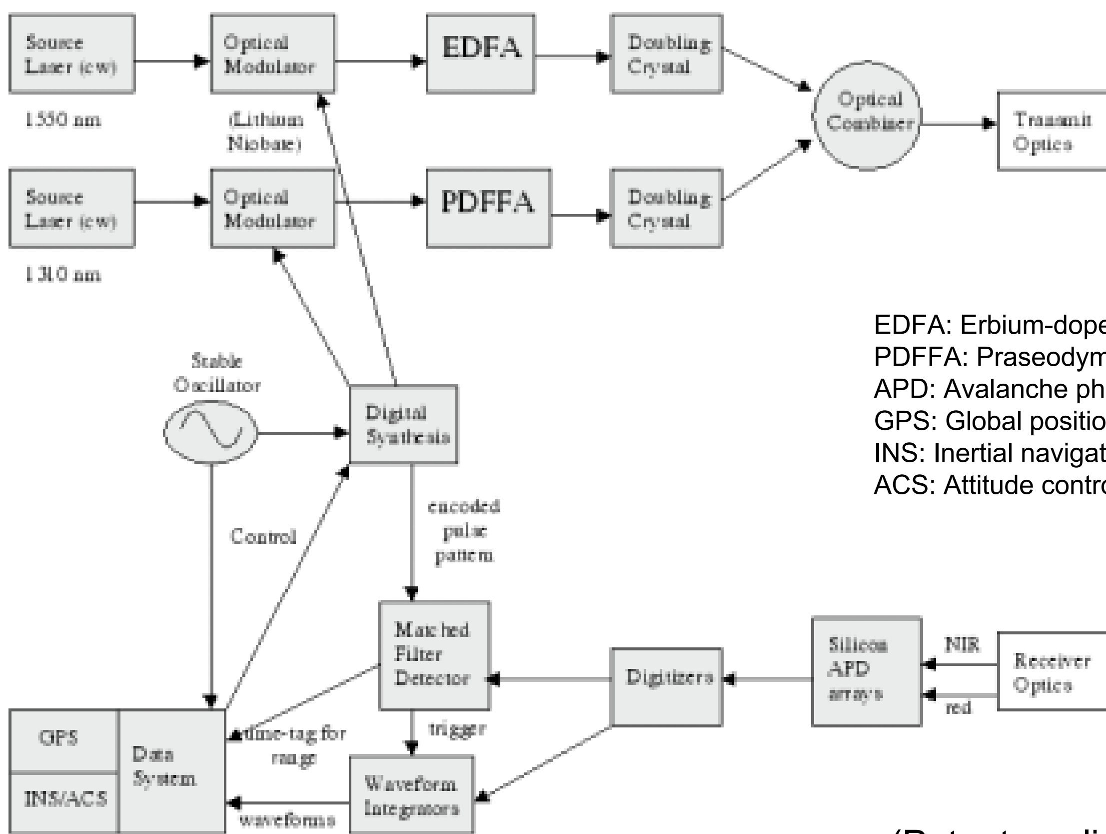


Frequency doubling crystal

Rall & Knox

Concept for a lidar system, using fiber-optic components from the telecommunications industry

Block Diagram: A Spectral-Ratio Biospheric Lidar



EDFA: Erbium-doped fiber amplifier.
PDFFA: Praseodymium-doped fluoride fiber amplifier.
APD: Avalanche photo-diode.
GPS: Global positioning system.
INS: Inertial navigation system
ACS: Attitude control system.

(Patent application filed.)